

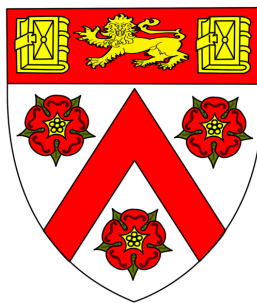
MULTI-DIMENSIONAL ANALYSIS OF THE
CHEMICAL AND PHYSICAL PROPERTIES
OF SPIRAL GALAXIES

Thesis submitted for the degree of
Doctor of Philosophy

by

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November 5, 2009

SUMMARY

The emergence of a new generation of instrumentation in astrophysics, which provide spatially-resolved spectra over a large 2-dimensional (2D) field of view, offers the opportunity to perform emission-line surveys based on samples of hundreds of spectra in a 2D context, enabling us to test, confirm, and extend the previous body of results from small-sample studies based on typical long-slit spectroscopy, while at the same time opening up a new frontier of studying the 2D structure of physical and chemical properties of the disks of nearby spiral galaxies. The project developed in this dissertation represents the first endeavour to obtain full 2D coverage of the disks of a sample of spiral galaxies in the nearby universe, by the application of the Integral Field Spectroscopy (IFS) technique. The semi-continuous coverage spectra provided by this spectral imaging technique allows to study the small and intermediate linear scale variation in line emission and the gas chemistry in the whole surface of a spiral galaxy.

The PPAK IFS Nearby Galaxies Survey: PINGS, was a carefully devised observational project, designed to construct 2D spectroscopic mosaics of 17 nearby galaxies in the optical wavelength range. The sample includes different galaxy types, including normal, lopsided, interacting and barred spirals with a good range of galactic properties and star forming environments, with multi-wavelength public data. The spectroscopic data set comprises more than 50 000 individual spectra, covering an observed area of nearly 100 arcmin², an observed surface without precedents by an IFS study. All sources of errors and uncertainties during the reduction process of the IFS observations are assessed very carefully. This methodology contributed not only to improve the standard reduction pipeline procedure for the particularly used instrument, improvements that can be applied to any similar integral-field observation and/or data reduction, but to defining a self-consistent methodology in terms of observation, data reduction and analysis for the kind of IFS surveys presented in this dissertation, as well as providing a whole new set of IFS visualization and analysis software made available for the public domain.

The scientific analysis of this dissertation comprises the study of the integrated properties of the ionized gas of the whole PINGS sample, and a detailed 2D study of the physical and chemical abundance distribution derived from the emission line spectra of four selected galaxies of the sample. Spatially-resolved maps of the emission line intensities and physical properties are derived for each the selected galaxies. Different methodologies are explored in order to study the spatially-resolved spectroscopic properties of the galaxies. Abundance analysis are performed based on a variety of diagnostic techniques using reddening corrected spectra. From this analysis, evidence is found to support that the measurements of emission lines of a “classical” H II region are not only aperture, but spatial dependent, and therefore, the derived physical parameters and metallicity content may significantly depend on the morphology of the region, on the slit/fibre position, on the extraction aperture and on the signal-to-noise of the observed spectrum. On the other hand, the results presented in this dissertation indicate the existence of non-linear *multi-modal* abundance gradients in normal spiral galaxies, consistent with a flattening in the innermost and outermost parts of the galactic discs, with important implications in terms of the chemical evolution of galaxies.

The powerful capabilities of wide-field 2D spectroscopic studies are proven. The chemical composition of the whole surface of a spiral galaxy is characterised for the first time as a function not only of radius, but of the intrinsic morphology of the galaxy, allowing a more realistic determination of their physical properties. The methodology, analysis and results of this dissertation will hopefully contribute in a significant way to understand the nature of the physical and chemical properties of the gas phase in spiral galaxies.

DECLARATION

I hereby declare that this thesis entitled *Multi-dimensional analysis of the chemical and physical properties of spiral galaxies* is not substantially the same as any that I have submitted for a degree or diploma or other qualification at any other University. I further state that no part of this dissertation has already been or is being concurrently submitted for any such degree, diploma or other qualification. This thesis is essentially the result of my own work, and includes nothing which is the outcome of work done in collaboration except where specifically indicated. Those parts of this dissertation which are undergoing review for publication, or included in conference proceedings are as follows:

- **Chapter 3**

The work presented in this chapter is essentially my own, it has been submitted for publication as: Rosales-Ortega, F. F., Kennicutt, R. C., Sánchez, S. F., Díaz, A. I., Pasquali, A., Johnson, B. D. and Hao, C. N., (2009) *PINGS: the PPAK IFS Nearby Galaxies Survey*, submitted to Monthly Notices of the Royal Astronomical Society, and it was benefited from collaboration with these authors.

- **Chapter 4**

The work presented in this chapter is essentially my own, a large part of it was submitted for publication in the article mentioned above. The work related to NGC 628 has been partially done within a collaboration, and submitted for publication as: Sánchez, S. F., Rosales-Ortega, F. F., Kennicutt, R. C., Díaz, A. I., Pasquali, A., Johnson, B. D. and Hao, C. N., (2009) *PPAK Wide-field Integral Field Spectroscopy of NGC 628: The largest spectroscopic survey on a single galaxy*, submitted to Monthly Notices of the Royal Astronomical Society. The *Gaussian-suppression* and absolute flux calibration techniques were developed in collaboration with S. F. Sánchez. Their implementation and initial testing were carried out in parallel by both of us, though the final implementation for this dissertation are my own work.

- **Chapter 5**

The work presented in this chapter is essentially my own. Some parts has been partially done within a collaboration, and submitted for publication in the articles mentioned above.

- **Chapter 6**

The work presented in this chapter is essentially my own, but benefited from discussions and advice from S. F. Sánchez and A. I. Díaz.

- Some figures of chapter 3 and chapter 6 have been included in *The Promise of Multiwavelength and IFU observations*, Kennicutt, R. C., Hao, C. N., Johnson, B. D., Rosales-Ortega, F. F., Díaz, A. I., Pasquali, A. and Sánchez, S. F., (2009) Proceedings of the IAU Symposium 262, G. Bruzual, S. Charlot, eds.

This thesis is less than 60 000 words in length.

Fernando Fabián Rosales Ortega
Cambridge, November 5, 2009

THESIS CONTENT

The whole thesis is not included in astro-ph due to file size limitations.

The full contents can be found at:

<http://www.dspace.cam.ac.uk/handle/1810/224843>

1

Introduction

The existence and distribution of the chemical elements and their isotopes in the universe is a consequence of very complex processes that have taken place in the past since the Big Bang and subsequently in stars and in the interstellar medium (ISM) of the present day galaxies, where they are still ongoing. These processes have been studied theoretically, experimentally and observationally. Different theories of cosmology, stellar evolution and interstellar processes have been considered, laboratory investigations of nuclear and particle physics, studies of elemental and isotopic abundances in the Earth and meteorites have also been involved, as well as astronomical observations of the physical nature and chemical composition of stars, galaxies and the interstellar medium.

From the observational point of view, the study of chemical abundances in galaxies, like many other areas of astrophysics, has undergone a remarkable acceleration in the flow of data over the last few years. We have witnessed wholesale abundances determinations in tens of thousands of galaxies from large scale surveys such as the Two Degree Field Galaxy Redshift Survey (2dFGRS, [Colless et al., 2001](#)) and the Sloan Digital Sky Survey (SDSS, [York et al., 2000](#)), measurements of abundances in individual stars of Local Group galaxies beyond the immediate vicinity of the Milky Way, and the determination of the chemical composition of some of the first stars to form in the Galactic halo. Chemical abundances studies are also increasingly being extended to high redshift, charting the progress of stellar nucleosynthesis over most of the age of the universe. The primary motivation common to all of these observational efforts is to use the chemical information as one of the means at our disposal to link the properties of high redshift galaxies with those we see around us today, and thereby understand the physical processes at play in the formation and evolution of galaxies.

The galactic chemical evolution is dictated by a complex array of parameters, including the local initial composition, star formation history (SFH), gas infall and outflows, radial transport and mixing of gas within disks, stellar yields, and the initial mass function (IMF). Although it is difficult to disentangle the effects of the various contributors, measurements of current elemental abundances constrain the possible evolutionary histories of the existing stars and galaxies. Important constraints on theories of galactic chemical evolution

and on the star formation histories of galaxies can be derived from the accurate determination of chemical abundances either in individual star-forming regions distributed across galaxies or through the comparison of abundances between galaxies. Nebular emission lines from individual H II regions have been, historically, the main tool at our disposal for the direct measurement of the gas-phase abundance at discrete spatial positions in low redshift galaxies.

However, in order to obtain a deeper insight of the mechanisms that rule the chemical evolution of galaxies, we require a significantly the number of H II regions sampled in any given galaxy. In this dissertation, I present a new observational technique conceived to tackle the problem of the 2-dimensional coverage of the whole surface of a galaxy. The advent of new spectroscopic techniques provides powerful tools for studying the small and intermediate scale-size variation in line emission and stellar continuum in nearby well-resolved galaxies. In this work, I address the problems and challenges that imply the determination of the chemical composition in galaxies in a 2D context and the subsequent derivation of their physical properties.

I will begin by presenting in this chapter a literature review on the determination of chemical abundances in galaxies. As an introduction to this topic, the physics of gaseous nebulae is discussed in § 1.1, together with a discussion of extra-galactic H II regions in § 1.2. The different methods of abundance determinations are presented in § 1.3. Physical properties derived from the determination of chemical abundances are discussed in § 1.4. These latter sections are partially based on the paper reviews and books about the physics and chemistry of the interstellar medium and H II extragalactic regions by [Dinerstein \(1990\)](#), [Pérez-Montero & Díaz \(2005\)](#), [Tielens \(2005\)](#), and [Osterbrock & Ferland \(2006\)](#). This discussion leads to the presentation of new techniques and methods for the determination of chemical abundances in nearby galaxies as described in § 1.5

1.1 The Physics of Gaseous Nebulae

Gaseous Nebulae are observed as bright extended objects in the sky, some are easily observed on direct images but many others are intrinsically less luminous or are affected by interstellar extinction on ordinary images, but can be resolved on long exposures with special filters and techniques so that the background and foreground stellar and sky radiations are suppressed. The surface brightness of a nebula is independent of its distance, but more distant nebulae have (on average) smaller angular size and greater interstellar extinction.

Gaseous nebula have emission-line spectra. Nebulae emit electromagnetic radiation over a broad spectral range, although only a few wavelengths pass easily through the Earth's atmosphere. Visible light and some infrared and radio radiation can be studied from the ground, but most other wavelengths can only be covered from high-latitude aircrafts or space telescopes. The source of energy that enables normal emission nebulae to radiate is ultraviolet radiation from stars within or near the nebula. There should be one or more stars with effective surface temperature $T_{\star} \geq 3 \times 10^4$ K, the ultraviolet photons of these stars transfer energy to the nebula by photoionization. In all nebulae, hydrogen (H) is by far the most abundant element, and photoionization of H is thus the main energy-input mechanism. Photons with energy greater than 13.6 eV (the ionization potential of H), are absorbed in the process, and the excess energy of each absorbed photon over the ionization potential appears as kinetic energy of a newly liberated photoelectron. Collisions between electrons and between electrons and ions, distribute this energy and maintain a Maxwellian velocity distribution with temperature T in the range $5,000 < T < 20,000$ K in typical nebulae. Collisions between thermal electrons and ions excite the low-lying energy levels of the ions. Downward radiation transitions

from these excited levels have very small transition probabilities, but at the low densities ($n_e \leq 10^4 \text{ cm}^{-3}$) of typical nebulae, collisional de-excitation is even less probable, so almost every excitation leads to emission of a photon, and the nebula thus emits a forbidden-line spectrum that is quite difficult to reproduce under terrestrial laboratory conditions.

Thermal electrons are recaptured by the ions, and the degree of ionization at each point in the nebula is fixed by the equilibrium between photoionization and recapture. In the recombination process, recaptures occur to excited levels, and the excited atoms thus formed then decay to lower and lower levels by radiative transitions, eventually ending in the ground level. In this process, line photons are emitted and this is the origin of the H I Balmer and Paschen line spectra observed in all gaseous nebulae. The recombination of H^+ gives rise to excited atoms of H^0 and thus leads to the emission of the H I spectrum. Likewise, He^+ recombines and emits the He I spectrum, and in the most highly ionized regions, He^{++} recombines and emits the He II spectrum. Recombination lines of trace elements are also emitted; however, the main excitation process responsible for the observed strengths of such lines with the same spin or multiplicity as the ground term is resonance fluorescence by photons, which is much less effective for H and He lines because the resonance lines of these more abundant elements have greater optical depth. Nevertheless, line emission of these rare elements plays a significant role in the physics of the nebula, and permits the determination of the chemical composition inside the nebula.

The spectra of gaseous nebulae are dominated by collisionally excited forbidden lines of ions of common elements, such as [O III] $\lambda\lambda 4959, 5007$ (the famous green nebular lines); [N II] $\lambda\lambda 6548, 6584$ and [S II] $\lambda\lambda 9069, 9523$ in the red; and [O II] $\lambda\lambda 3727, 3729$ in the ultraviolet (which normally appears as a blended $\lambda 3727$ line on low-dispersion spectrograms). In addition, the permitted lines of hydrogen, $\text{H}\alpha$ $\lambda 6563$ in the red, $\text{H}\beta$ $\lambda 4861$ in the blue, $\text{H}\gamma$ $\lambda 4340$ in the violet and so on, are characteristic features of every nebular spectrum, as is He I $\lambda 5876$, which is considerably weaker, while He II $\lambda 4686$ occurs only in higher-ionization nebulae. Long-exposure spectrophotometric observations extending to faint intensities show progressively weaker forbidden lines, as well as faint permitted lines of common elements such as C II, C III, C IV and so on. Nebular emission-line spectra extend into other spectral ranges, in the infrared for example, the [Ne II] $\lambda 12.8 \mu\text{m}$ and [O III] $\lambda 88.4 \mu\text{m}$ are among the strongest lines measured, into the ultraviolet Mg II $\lambda\lambda 2796, 2803$, C III] $\lambda\lambda 1907, 1909$, C IV $\lambda\lambda 1548, 1551$ and Ly α $\lambda 1216$ are also observed. It is often necessary to obtain spectra outside the traditional visible/near spectral bands to get an accurate picture of the system in question.

Gaseous nebulae have weak continuous spectra, consisting of atomic and reflection components. The atomic continuum is emitted chiefly by free-bound transitions, mainly in the Paschen continuum of H I at $\lambda > 3646 \text{ \AA}$, and the Balmer continuum at $912 \text{ \AA} < \lambda < 3646 \text{ \AA}$. In addition to the bright-line and continuous spectra emitted by atomic processes, many nebulae have reflection continua arising from starlight scattered by dust. The amount of dust varies from nebula to nebula, and the strength of this continuum fluctuates correspondingly. In the infrared for example, the nebular continuum is largely thermal radiation emitted by dust particles heated to a temperature of order 100 K by radiation derived originally from the central star.

Gaseous nebula may be classified into two main types: H II regions and planetary nebulae (PNe). Though the physical processes in both types are quite similar, the two groups differ greatly in origin, mass, evolution and age. The objects of study for the chemical composition of galaxies are extragalactic H II regions. These diffuse nebulae are regions of interstellar gas in which the exciting stars are O- or early B-type stars, i.e. young stars which use up their nuclear energy quickly. These hot, luminous stars undoubtedly formed fairly recent from interstellar matter that would be otherwise be part of the same nebula. The effective temperature

of the stars are in the range $3 \times 10^4 < T_* < 5 \times 10^4$ K; throughout the nebula, H is ionized, He is singly ionized and other elements are mostly singly or doubly ionized. Typical densities in the ionized part of the nebula are of the order 10 or 10^2 cm^{-3} , ranging to high as 10^4 cm^{-3} . In many nebulae, dense neutral condensations are scattered through the ionized volume. Internal motions occur in the gas with velocities of order 10 km s^{-1} , approximately the isothermal sound speed. Bright rims, knots, condensations, and so on, are apparent to the limit of resolution. The hot, ionized gas tends to expand into the cooler surrounding neutral gas, thus decreasing the density within the nebula and increasing the ionized volume. The outer edge of the nebula is surrounded by ionization fronts running out into the neutral gas. This original two-phase model of the interstellar medium (the H II /H I region dichotomy) was introduced by [Strömgren \(1939\)](#). He showed that photoionized gas near hot stars is segregated into physically distinct volumes, separated from their neutral environment by sharp boundaries.

1.1.1 Extragalactic H II regions

The spectra of H II regions are strong in H I recombination lines, [N II], [O II] and [O III] collisionally excited lines, but the strengths of N and O may differ greatly, being stronger in the nebulae with higher central-star temperatures. The brightest H II regions can easily be seen on almost any large-scale image of nearby galaxies, and those taken in a narrow wavelength band in the red (including H α and [N II] lines) are specially effective in showing faint and often heavily obscured extragalactic H II regions. The H II regions are strongly concentrated to the spiral arms and indeed are the best objects for tracing the chemical composition, structure and dynamics of the spiral arms in distant galaxies. They trace recent star formation and, through the analysis of their chemical composition, previous star formation activity. Typical masses of observed H II regions are of the order 10^2 to $10^4 M_\odot$, with the lower limit depending largely on the sensitivity of the observational method used.

H II regions are the only form of interstellar material which emits strongly in the optical spectral region; therefore, there is a much longer and richer history of observations and theory for them than for the other thermal phases of interstellar matter. Optical observations of H II regions provide fairly complete information about their elemental composition. From their spectra, abundances relative to hydrogen can be estimated for nearly all of the most common elements, particularly He, N, O, Ne, Ar, and S (note that oxygen alone constitutes nearly 50% by mass of the elements heavier than helium.) Furthermore, ionized nebulae are remarkably efficient machines for converting ultraviolet continuum energy from OB stars, originally diluted over wide bandpasses, into a few narrow, intense, optically-thin emission lines. The intrinsic emissivities of these lines are easy to calculate in principle, although they are sensitive to the local thermodynamic state of the gas (electron density n_e and temperature T_e). On the other hand, the thermal parameters can also be determined from the spectra, using diagnostic line-intensity ratios. In this way, H II regions can be used to measure element abundances in the (present-day) gas of distant galaxies.

The sample of extragalactic H II regions studied so far has metal abundances ranging from about 0.02 to several times solar. This is a useful complement to studies of our own Galaxy, which contains no severely metal-deficient H II regions (except for a handful of planetary nebulae formed by stars of the halo population). In contrast, for many H II regions in the outskirts of late-type spirals and in some dwarf irregular galaxies, the process of metal enrichment by stellar nucleosynthesis is still in its early stages, providing a hint on the early chemical evolution of galaxies. These low-metallicity H II regions are also presumed to have experienced only a small degree of alteration in their helium abundances due to stellar activity. There-

fore, their present He/H ratios should be nearly the same as the primordial value, providing valuable tests for cosmological theories. The various *categories* of extragalactic H II regions are essentially lists of their environments. These include:

1. Disk H II regions in spiral and irregular galaxies.
2. Gassy dwarf irregular galaxies with spectra which are heavily dominated by H II regions.
3. Nuclear and near-nuclear regions sometimes called “starburst” or “hotspot” H II regions (e.g. [Kennicutt et al., 1989](#)).

The first two categories have the best abundance data available in the literature. Regions in the third group tend to have relatively strong stellar continua and to be fairly metal-rich, which make it difficult to obtain accurate measurements of the emission lines from which abundances are determined. On the other hand, members of the first two categories are universally regarded as members of the same family. H II regions in nearby galaxies have been well-catalogued; atlases are available for the Large and Small Magellanic Clouds (LMC, SMC), and a large number of other galaxies (e.g. [Hodge & Wright, 1967, 1977](#); [Hodge & Kennicutt, 1983](#)). The star-forming dwarf irregulars are usually found by spectroscopic surveys for emission-line galaxies (e.g. [Kinman 1984](#) and more recently the SDSS data releases).

The statistical properties of the H II region populations in spiral and irregular galaxies were addressed by [Kennicutt \(1988\)](#) and [Kennicutt et al. \(1989\)](#). They find that late-type galaxies have both intrinsically higher-luminosity H II regions, and larger total numbers of H II regions after normalization by galaxy size, than do early-type spirals. Within a galaxy, the differential luminosity function of the H II regions is roughly a power-law, $N \propto L^{-2 \pm 0.5}$, although some low-luminosity irregulars have an exceptional supergiant complex, and Sa-Sb galaxies are deficient in luminous regions. While the positive correlation between the luminosity of the brightest H II region and that of the parent galaxy can be understood as chiefly a sample-size effect, the dependence on morphological type is a real and separate factor. Typical large galaxies contain hundreds of optically detectable H II regions. It is important to note that of all the regions detected and cataloged in H α or H β , it is usually the nearest and the most luminous “giant” H II regions for which abundances are derived.

Some of the best-studied regions are the 30 Doradus complex in the LMC, NGC 604 in M 33, and NGC 5461 and 5471 in M 101. Selection effects play an important role, necessarily poorer spatial resolution contributes to a tendency to identify larger regions in more distant galaxies. This effect is illustrated by [Israel et al. \(1975\)](#), who compare large-beam radio measurements with optical images of the same H II regions in M 101; at better resolution these regions break up into groups or chains of smaller clumps. Likewise, H II regions in dwarf irregulars are also found to have complex structure when closely examined (e.g. [Hodge et al., 1989](#); [Davidson et al., 1989](#)). In more distant galaxies, we will always be looking at more heterogeneous volumes; for example, a typical aperture size (4”) for spectrophotometric studies corresponds to 1 pc at 50 kpc (the LMC) and 2 kpc at 100 Mpc.

The morphology of many giant extragalactic H II regions can be characterized to first order as a “core-halo” structure, on the basis of both optical and radio-continuum data. The cores are composed of dense material, often in several distinct clumps, close to the ionizing stars. The diffuse, lower-density envelopes are presumably ionized by photons escaping from the inner regions and represent the radiation-bounded edges of the Strömgren volume. Most giant extragalactic H II regions are believed to be essentially radiation-bounded (e.g. [McCall et al., 1985](#)). In addition, the denser regions themselves are inhomogeneous, as seen

in the detailed studies of NGC 5471 by Skillman (1985), and of NGC 604 by Diaz et al. (1987). That there are also inhomogeneities on smaller spatial scales is shown by the discrepancy between (rms) n_e values derived from recombination emission and local values determined from density-sensitive line ratios. The dense clumps are embedded in a much lower-density medium, with typical clump volume filling factors of 0.01 – 0.1 (e.g. Kennicutt, 1984; McCall et al., 1985). The interclump material is often treated as a vacuum in nebular models, because it does not contribute significantly to the optical emission lines.

Giant extragalactic H II regions display supersonic velocities, which appear to correlate with $H\beta$ luminosity. Terlevich & Melnick (1981) interpret the line-widths as virial and therefore usable for determining the local gravitational field; they also find a secondary dependence on metallicity. An alternative interpretation of the origin of the line-widths is that they are a result of stellar winds from the exciting stars, and possibly also from embedded supernova remnants (e.g. Dopita, 1981; Skillman, 1985). For nearby regions, it is possible to actually identify the stars which may be responsible for driving the high-velocity gas.

As mentioned above, luminous extragalactic H II regions are ionized by OB associations. For nearby regions, the members of the stellar cluster can be distinguished individually and HR diagrams can be constructed. The nebular ionization structure and emitted spectrum will evolve as the cluster ages and the UV radiation field diminishes and softens. Wolf-Rayet stars are often present in extragalactic H II regions, the frequency of Wolf-Rayet stars is higher for higher-metallicity regions as proved by Maeder et al. (1980). Wolf-Rayet stars are important in this context because they furnish metal-rich outflows which are capable of altering the chemical composition of their gaseous environment. Giant H II regions are also known hosts of Type II supernovae. Winds and supernovae from the massive stars can contaminate (or enrich) the local gas in H II regions in He, C, O, and other species. Evidence for such local enrichments has been sought and perhaps seen in some regions (Skillman, 1985; Pagel, 1986).

1.2 Determination of chemical abundances in H II regions

H II regions are ideal places to determine the abundance of the elements that are responsible for recombination and fine-structure lines. The list of these elements is generally limited at the present time, although lines of many more elements are observable in several planetary nebulae and high spectral resolution and multi-wavelength studies of nearby H II regions (e.g. García-Rojas et al., 2006). The determination of element abundances in H II regions are given relative to the hydrogen content, which is observed by its recombination lines. Only a few abundant elements give observable recombination lines with similar physics: helium, carbon, nitrogen and oxygen, whose lines are very weak to detect and may suffer problems with fluorescence excitation. The abundances derived from the fine-structure lines in the visible are sensitive to both temperature and density, and the interpretation of the line intensities is a delicate problem. In some cases, the temperature of the emitting zone can be obtained and the abundance determination is safer. However, even in this case temperature fluctuations can yield systematic errors in the abundances.

The abundances derived from the mid-and far-infrared fine structure lines are not sensitive to electron temperature and are little affected by extinction. These are considerable advantages with respect to the optical lines. However, there are important discrepancies between the abundances derived from infrared and from optical lines. These differences may originate in temperature fluctuations or in errors in atomic parameters, but one has to consider that the critical density for infrared lines is generally much smaller than for visible lines, so that the abundances derived from the infrared lines are underestimated if the density is high (this effect can be important for planetary nebulae).

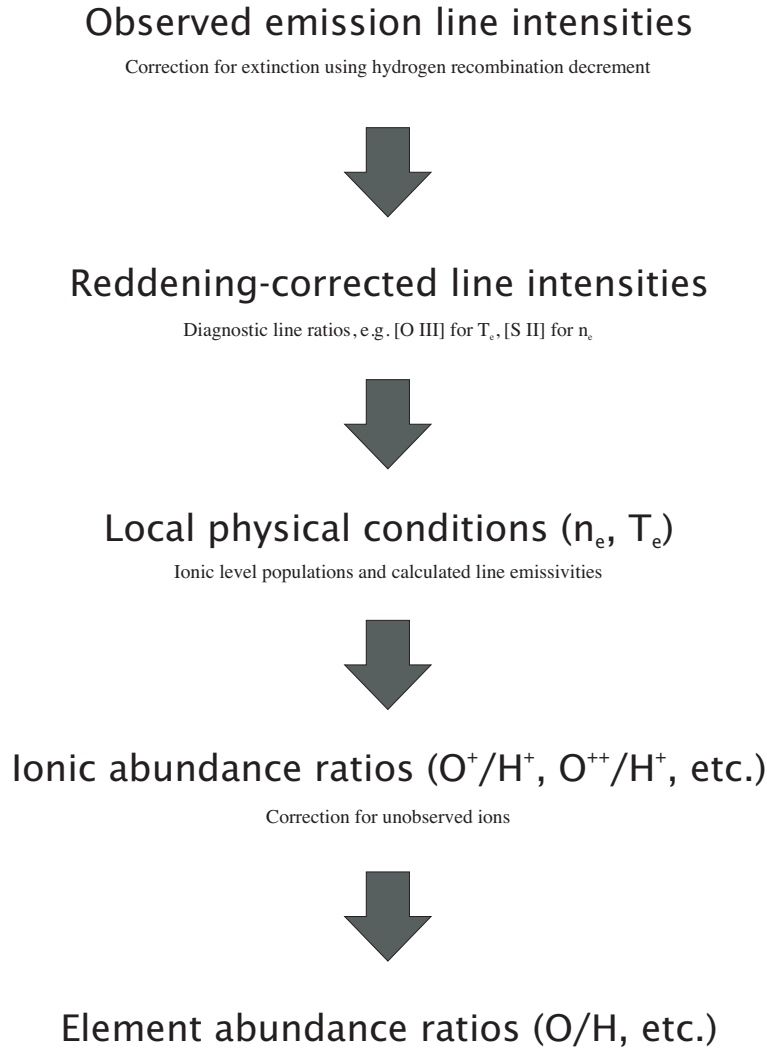


Figure 1.1: The *direct method* of chemical abundance determinations.

All elements (with the obvious exception of H) exist in several ionization states in H II regions. However, only the abundances of those ions that emit observable lines can be determined. If such ions are minor species, they yield no useful information because the physical parameters of H II regions are most often too uncertain to allow an accurate solution of the ionization equilibrium. This is for example the case for O I, C II, S II or Si II. If the observed ion is a major species the situation is more favorable since we can calculate, more or less accurately, the abundances of the unobserved ions of the same element. However, uncertainties remain if a high precision is required, as is the case of helium in a cosmological context. The most favorable case is that of oxygen, whose major ionization states, O II and O III, are observable optically and for which the electron temperature T_e can be determined. For this reason, oxygen is, after helium, the element whose abundance is best determined, at least if the temperature is large enough (or the metallicity is too low) for the temperature-sensitive lines (e.g. [O III] $\lambda\lambda 4363$) to be measured. If this is not the case, we may construct tailored models of the nebular ionization and thermal structure of a H II region to estimate the electron temperatures and ionization correction factors for individual ions.

However, given the difficulty of detecting the T_e -sensitive line and the assumptions made in nebular modeling, a very popular approach is to obtain the abundance of extragalactic H II regions using empirical relations between the oxygen abundance and the intensity of the [O II] $\lambda\lambda 3726, 3729$ and [O III] $\lambda\lambda 4959, 5007$

lines relative to $H\beta$ (Pagel, 1997) or by using the $[O II] \lambda\lambda 7320, 7330$ as described by Aller (1984) and implemented by Kniazev et al. (2004) in SDSS H II galaxies. This method however, is the less accurate and much discussion about the reliability of the different empirical calibrations is still ongoing in the literature (e.g. see Kewley & Ellison, 2008, for a thorough discussion). A full discussion regarding this topic is beyond the scope of this chapter, however, in ??, I include a small review on the different empirical techniques of abundance determinations (considering their particular advantages and pitfalls), and their implementations in the context of the work carried out in this dissertation. A more complete explanation of the determination of nebular abundances from emission lines can be found in references on the physics of gaseous nebulae such as Aller (1984), and Osterbrock & Ferland (2006).

1.3 Abundance gradients in galactic disks

It has been noticed that certain H II region emission-line ratios, such as $[O III]/H\beta$, vary across the disks of nearby spiral galaxies. The interpretation of this variation in terms of a metallicity trend was introduced by Searle (1971), in a paper that laid the groundwork for the entire field of abundance gradients. It was soon followed up by further observational studies and a more rigorous analysis involving the construction of realistic nebular models (Shields, 1974). From the start it was recognized that there was a need for a “second parameter” in addition to the O/H ratio, to explain an observed systematic increase in O^{++}/O^+ with decreasing O/H. Shields & Tinsley (1976) suggested that this secondary effect results from a tendency for the effective temperatures of the ionizing stars to be hotter for lower O/H, and interpreted it as a metallicity-dependent truncation of the top end of the initial mass function (i.e. that the formation of very massive stars is inhibited by higher metallicity). Some form of the idea of a Z-dependent IMF is still a popular interpretation of the “excitation” trend (e.g. Vilchez & Pagel, 1988), but it is also the case that a similar effect can arise from systematic variations in the nebular geometry and/or filling factor (Mathis, 1985; Dopita & Evans, 1986).

An extensive body of literature has been amassed on the subject of abundance gradients in galaxies. Not surprisingly, many works have focused on large, nearby galaxies with many observable H II regions, such as M 33 (Vilchez et al., 1988; Rosolowsky & Simon, 2008) and M 101 (Evans, 1986; Torres-Peimbert et al., 1989; Kennicutt & Garnett, 1996). The gradients are usually expressed as a logarithmic fit to some 5–20 regions per galaxy, and have a magnitude of about $\delta \log(O/H)/R = -0.08 (\pm 0.03)$ dex/kpc. This is similar to the values derived for the solar-neighborhood metallicity gradient in the Milky Way galaxy. The trend of these gradients in the inner parts of galactic disks are difficult to study, both because the H II region samples are often small, and more fundamentally because these are generally the most metal-rich regions, for which $[O III] \lambda 4363$ is unobservable and therefore the derived abundances are heavily model-dependent.

The steepest abundance gradients were initially seen in late-type spiral galaxies (types Sb-Scd). Irregulars and barred spirals tend to have weak or zero radial gradients. Early type spirals are harder to study because their H II regions are intrinsically fainter, but studies of M 81 (Sab) show it to have an O/H gradient similar to those of M 33 and M 101 (Garnett & Shields, 1987). There is at present no convincing evidence that the O/H gradient depends on morphological type among spiral galaxies. However, there is evidence for a good correlation between mean O/H abundance and the overall galaxy mass or luminosity. This trend resembles the correlation of stellar metallicity with galaxy mass, and probably has its roots in the fundamental processes of galaxy formation and evolution.

Along with the trend in $[O III]/H\beta$, a similar radial trend was noted for the ratio $[N II]/H\alpha$, which de-

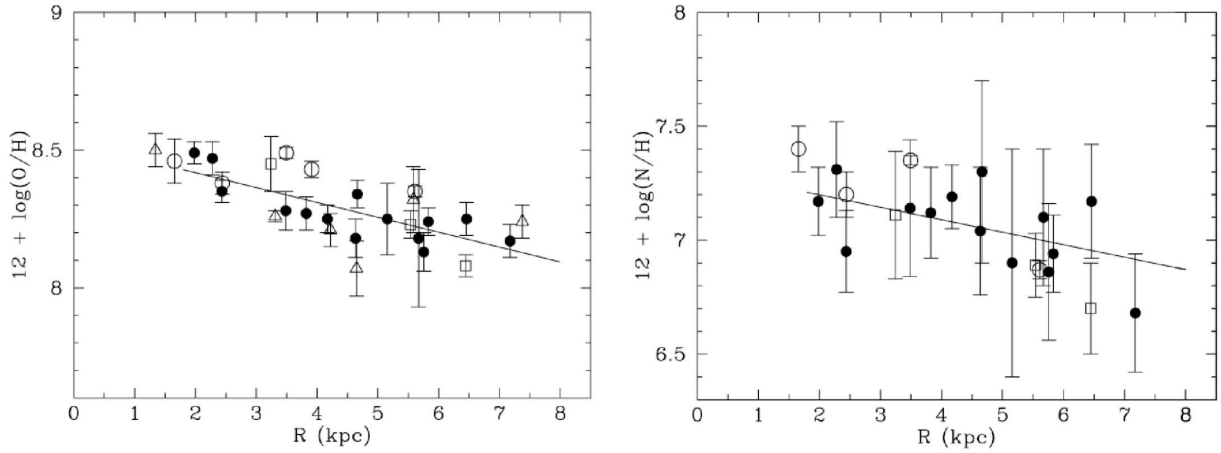


Figure 1.2: The O/H and N/H abundance vs. galactocentric distance in M 33, examples of the radial oxygen and nitrogen abundance gradients. Plots taken from [Magrini et al. \(2007\)](#).

creases with increasing distance from the centers of spiral galaxies. Although part of this trend is due to the generally lower degree of ionization in the outer H II regions, there also must be a real variation in abundance. Unlike oxygen, for nitrogen one usually can measure the singly-ionized state only; unfortunately, N^{++} has no strong optical lines. As mentioned before, the nitrogen abundance is basically derived from $[\text{N II}]/[\text{O II}]$. The relative behavior of O and N is often displayed by plotting N/O vs. O/H. Some studies find that N/O varies almost as steeply as O/H, which has special significance in the context of chemical evolution models, but others claim that N/O varies only slightly or is constant across the disks of galaxies such as M 101, M 33, M 81, and M 83. There also appear to be variations in N/O at a given O/H from galaxy to galaxy (same references as above). Some of these variations may be an artifact of the analysis, especially since N^+ contains only a small fraction of the nitrogen for the lowest-abundance, most highly ionized regions. For such regions, the ionization correction factors are very large, and the uncertainties in the ionization structure translate into large uncertainties in the elemental abundance of nitrogen. Nevertheless, there is accumulating evidence that nitrogen has a more complicated behavior than does oxygen, with N/O being roughly constant at low values of O/H and increasing at higher O/H (e.g. [Pagel, 1985](#); [Torres-Peimbert et al., 1989](#)). Measurements of N/O in metal-poor dwarf irregular galaxies are an important ingredient in this argument.

Scatter in gradient determinations has been seen in various studies (e.g., in the Milky Way [Afflerbach et al. 1997](#) or in M 33 [Rosolowsky & Simon 2008](#)), even after accounting for uncertainties in the stellar absorption and reddening corrections, an intrinsic scatter of ~ 0.1 dex has been measured in these very well-studied galaxies which is unexplained by the measurement uncertainties. Regardless of its source, gradient determinations made in the face of significant scatter coupled with a limited number of observations may produce widely varying results. This historical evolution of the gradient determination ranging over nearly an order of magnitude, should serve as a cautionary example. Only large numbers of measurements can overcome the uncertainties engendered by the intrinsic variance, as some observations suggest that the uncertainties in the gradients are systematically underreported.

1.3.1 The Galactic abundance gradient

Because of interstellar extinction, one can use the same techniques as for extragalactic H II regions only for the part of our Galaxy outside a galactocentric distance of about 7 kpc. Studies such as those by [Hawley \(1978\)](#) found gradients similar to those in other spirals, $\delta \log(\text{O}/\text{H})/\delta R = -0.04$ to -0.06 dex/kpc and $\delta \log(\text{N}/\text{H})/\delta R = -0.10$ dex/kpc. Determination of abundances in the inner galaxy requires the use of other techniques, such as measuring electron temperatures from radio recombination lines. The values of T_e are found to increase systematically with increasing radius, presumably because of a decreasing abundance of oxygen, the primary coolant. The inferred gradient in O/H is $\delta \log(\text{O}/\text{H})/\delta R = -0.07$ dex/kpc after the classic paper of [Shaver et al. \(1983\)](#).

The results from optical studies for the other measurable elements are similar to those for other galaxies: N/H varies more steeply than O/H; S/O, Ne/O, and Ar/O do not vary in the outer part of the Galactic disk. Again, the optical studies are restricted to the unobscured portion of the Milky Way galaxy, and therefore do not sample the inner disk where the inferred O/H values are high. A more recent development, made possible by improvements in infrared detectors and the availability of space observatories. The exploration of the infrared spectral region as a tool for studying the galactic abundance gradient. The mid-infrared spectral region (5-30 μm) contains emission lines of the major ions of Ar, S, and Ne: [Ar II] 7.0 and [Ar III] 9.0 μm ; [S III] 18 and [S IV] 10.5 μm ; and [Ne II] 12.8 μm . These lines have been measured in a number of H II regions in the inner Galaxy, and evidence for abundances elevated by factors of two or three have been found for the Galactic Center and for H II regions in the 5 kpc “ring” region ([Pipher et al., 1984](#)).

However, even these mid-infrared lines suffer somewhat from extinction. In particular, the [Ar III] and [S IV] lines fall in the middle of the strong 10 μm silicate absorption feature, where the optical depth is comparable to that in the near-infrared. Another approach to studying abundances in the inner galaxy is to make use of the fine-structure lines of [O III] 52, 88 μm and [N III] 57 μm . By a happy coincidence, these lines from the abundant and (presumably) usually co-extensive O^{++} and N^{++} ions fall close together in wavelength and have fairly similar dependences on the electron density. The line emissivities are also essentially independent of the electron temperature. Measurements of these three lines therefore yield a relatively accurate value for the N/O ratio. A survey of about a dozen galactic H II regions in these lines yielded strong evidence that N/O in the Galactic Center and 5 kpc “ring” is elevated by a factor of 2 or 3 as compared to the solar neighborhood. There remain some unsettled questions regarding N/O determinations from the far-infrared lines, including possible ionization structure effects in H II regions ionized by very cool stars and a systematic discrepancy between values derived from the infrared lines and those derived optically from [N II]/[O II] ([Rubin et al., 1988](#)).

More recent observations of IR fine-structure lines of the [S III] 19 μm , [O III] 52 and 88 μm , and [N III] 57 μm in compact H II Galactic regions have found abundance gradients of the form $[\text{S}/\text{H}] = (-4.45 \pm 0.04) - (0.063 \pm 0.006) (\text{kpc})$, $[\text{N}/\text{H}] = (-3.58 \pm 0.04) - (0.072 \pm 0.006) (\text{kpc})$, and $[\text{O}/\text{H}] = (-2.85 \pm 0.06) - (0.064 \pm 0.009) (\text{kpc})$ ([Afflerbach et al., 1997](#)). These abundances are consistent with production of sulphur, nitrogen, and oxygen by primary nucleosynthesis. Comparison with abundances in other galaxies implies a Hubble type between Sab and Sb for our Galaxy and an unbarred or mixed galactic structure ([Vila-Costas & Edmunds, 1992](#)).

1.4 Comparison with Chemical Evolution Models

The recognition of significant variations in the gas composition within and among galaxies, along with parallel results on the stellar populations, inspired the development of chemical evolution models which attempt to explain these patterns. The so-called “simple model” postulates a closed system of gas and stars, which self-enriches in metals as generations of stars age, die, and seed the ambient gas in the heavy elements (Searle & Sargent, 1972). This model also makes the approximations that the stellar lifetimes and timescale for complete mixing of nucleosynthetic products are negligible in comparison to the timescale on which the metallicity evolves (“instantaneous recycling”). The simple model makes a specific prediction regarding the metallicity and system properties:

$$Z = y \ln(M_{\text{total}}/M_{\text{gas}}), \quad (1.1)$$

in this equation Z is the metal abundance, y is the fraction of the stellar mass converted to heavy elements (the *yield*), and $M_{\text{total}} = M_{\text{gas}} + M_{\text{stars}}$.

Although this model is most appropriate for the low-mass galaxies, it can also be applied to large disk galaxies if concentric radii are treated as independent zones. However, it does not explain the observed gradients, so modifications such as radial flows, matter exchange with an outside reservoir (infall and outflow), or a variable stellar initial mass function, have been proposed as modifications to the model (Matteucci & Francois, 1989; Dopita, 1990).

The relative abundances of nitrogen and oxygen are of particular interest, since they are synthesized in different astrophysical sites. Oxygen is synthesized in massive stars and distributed into the interstellar medium by Type II supernovae, while the origin of nitrogen is more problematic. A distinction is frequently made between “primary” nucleosynthetic products, which can be synthesized directly from H and He in Population III stars, and “secondary” products, which require a “seed” heavy nucleus to be initially present in the star where its synthesis occurs. By this definition, oxygen is a primary species. Nitrogen is secondary when made as a by-product of CNO-cycle hydrogen burning. According to the simple closed-box model, the abundance of a secondary species is quadratic, so that if N is secondary and O primary, then $(\text{N}/\text{H}) \propto (\text{O}/\text{H})^2$, or $(\text{N}/\text{O}) \propto (\text{O}/\text{H})$. The N/O ratio does appear to approach this behavior, for H II regions with moderately high O/H values in M 101 (Torres-Peimbert et al., 1989) and in the Milky Way. However, below a certain values of O/H, it appears that N/O is constant; these low-metallicity H II regions occur mostly in low-mass galaxies. Thus, it is becoming clear that nitrogen is not purely a secondary nucleosynthetic product. Indeed, N may be produced within intermediate-mass stars by an effectively primary process, if C synthesized within the star by the triple-alpha reaction is later subjected to the CN cycle. Nitrogen made by this process would be primary, but there might be a time-delay in building up its abundance relative to the nuclear products of supernovae, because of the longer lifetimes of the source stars.

The other elements measured in extragalactic H II regions, S, Ne, and Ar, are not likely to be dominated by secondary processes. They might still, however, vary differently than oxygen, if they were produced in stars of different mass ranges and the IFM varied or the timescales for enrichment differed substantially. There are known variations in the abundance ratios of certain elements. For example the fact that the iron-group is deficient relative to oxygen in Population II stars is thought to reflect an origin for the former chiefly in Type I supernovae, which originate in long-lived progenitors, as opposed to synthesis of oxygen in massive stars and Type II supernovae.

In the context of chemical evolution models, [Garnett \(2002\)](#) studied the metallicity-luminosity and metallicity-rotation speed correlations for spiral and irregular galaxies for a sample of spiral and irregular galaxies having well-measured abundance profiles, distances, and rotation speeds. He finds that the $O/H-V_{rot}$ relation shows a change in slope at a rotation speed of about 125 km s^{-1} . At faster V_{rot} , there appears to be no relation between average metallicity and rotation speed. At lower V_{rot} , the metallicity correlates with rotation speed. This change in behavior could be the result of increasing loss of metals from the smaller galaxies in supernova-driven winds. The idea was tested by looking at the variation in effective yield, derived from observed abundances and gas fractions assuming closed box chemical evolution. The effective yields derived for spiral and irregular galaxies increase by a factor of 10-20 from $V_{rot} \sim 5$ to 300 km s^{-1} , asymptotically increasing to approximately constant y_{eff} for $V_{rot} \sim 150 \text{ km s}^{-1}$. The trend suggests that galaxies with $V_{rot} \sim 100\text{-}150 \text{ km s}^{-1}$ may lose a large fraction of their supernova ejecta, while galaxies above this value tend to retain metals. The determination of effective yields as function of galactic radius and its interpretation stands as one of the main studies in order to discriminate among different physical effects which may affect the chemical evolution of a galaxy.

1.5 Goals of this dissertation

As described in this chapter, the study of chemical abundances has undergone a remarkable development in the last decades thanks mostly to important observational efforts that have focused on the derivation of physical and chemical properties of emission line H II regions in galaxies by spectroscopic techniques. The main motivation common to all of these observations is to use the chemical information as one of the means at our disposal to understand the physical processes at play in the formation and evolution of galaxies in the universe.

Hitherto, most spectroscopic studies in nearby objects have been limited by the number of objects sampled, the number of H II regions observed and the coverage of these regions within the galaxy surface. In order to increase significantly the number of H II regions sampled in any given galaxy we require the combination of high quality multi-wavelength data and wide field spectroscopy. The advent of multi-object and integral field spectrometers with large field of view now offer us the opportunity to undertake a new generation of observations, based on samples of scores to hundreds of H II regions and full 2-dimensional (2D) coverage. These sort of data would enable to test, confirm and extent the previous body of results from small sample studies, while at the same time open up a new frontier of studying the 2D metallicity structure of disks and the intrinsic dispersion in metallicity, or to test and strengthen the diagnostic methods that are used to measure the H II region abundances in galaxies, among other issues.

The scientific core of this dissertation is based on an observational project conceived to tackle the problem of the 2D spectroscopic coverage of the whole galaxy surface. New techniques in imaging spectroscopy (or integral field spectroscopy, IFS) provide a powerful tool for studying the small and intermediate scale-size variation in line emission and stellar continuum in nearby well-resolved galaxies. We designed a project to take advantage of these new observational techniques in order to assemble a unique spectroscopic sample from which we could study, with unprecedented detail, the star formation and gas chemistry across the surface of a galaxy. The observations consist of Integral Field Unit (IFU) 2D spectroscopic mosaics of a representative sample of nearby galaxies ($D < 100 \text{ Mpc}$) with a projected angular size of less than 10 arcmin . The mosaics were constructed using the unique instrumental capabilities of the Postdam Multi Aperture Spectrograph, PMAS ([Roth et al., 2005](#)) in the PPAK mode ([Verheijen et al., 2004](#); [Kelz & Roth,](#)

2006) at the German-Hispanic Astronomical Centre at Calar Alto (CAHA), Spain. The PMAS fibre PAcK (PPAK) is one of the world's widest integral field unit with a field-of-view (FOV) of 74×65 arcseconds that provides a semi-contiguous regular sampling of extended astronomical objects. This project represents the first attempt to obtain 2D spectra of the whole surface of a galaxy in the nearby universe. The spectroscopic mosaicing comprises more than 50 000 spectra in the optical wavelength range.

This observational project was devised as a scientific international consortium, the members are world-leading experts in their respective fields, including star formation and chemical abundances of galaxies, active galactic nuclei, multiwavelength observations of emission line regions and 2D spectroscopy. The project was entitled: the **PPAK IFS Nearby Galaxies Survey**, or **PINGS**. The P.I. of this project is Prof. Robert C. Kennicutt Jr. at the Institute of Astronomy, University of Cambridge. The collaborators of the consortium are: Dr. Ángeles Díaz at the Universidad Autónoma de Madrid, Spain; Dr. Anna Pasquali at the Max-Planck Institut für Astronomie in Heidelberg, Germany; Dr. Sebastián S. Sánchez at CAHA, Spain; Benjamin Johnson and Caina Hao at the University of Cambridge, UK.

The primary scientific objectives of this dissertation are to use the PINGs observations to obtain pixel-resolved emission-line maps across the disks of the galaxies to study the 2D abundance distribution and on characterising the relations between these abundance properties and the physical properties of the parent galaxies. By targeting virtually every H II region in the galaxies, as a consequence of the nearly complete spatial coverage of the IFUs, we are able to test for the first time the systematic dependences of the strong-line abundances on the size, luminosity, surface brightness, and other properties of the H II regions. In that respect, the PINGs observations and the subsequent analysis represent a leading leap in the study of the chemical abundances and the global properties of galaxies, information which is most relevant for interpreting observations at all redshift sources accessible with the current technology.

1.5.1 Structure of the dissertation

The structure of this thesis is as follows: In § 2, I discuss the importance of Integral Field Spectroscopy (IFS) in astrophysics, including an explanation of the technique with their advantages and pitfalls, a description of the available instrumentation in the world by the time this project was envisaged, and the selection criteria of the telescope-instrument chosen for this project. I also include a brief review to previous works that have attempted to obtain 3D chemical abundance information in galaxies. In § 3, I present the sample of galaxies and the selection criteria followed according to the scientific objectives established for this dissertation. This chapter also includes a full description of the logistics and observations, explaining the telescope set-up and the particular observing technique adopted for this project. In § 4, I explain the reduction process of the IFS raw data, the additional corrections implemented in this project and the improvements with respect to previous pipelines, particularly regarding the flux calibration and the sky-subtraction. The possible sources of errors and uncertainties are addressed, together with an explanation of the techniques implemented to minimise them. In § 5, I present the integrated spectra of the PINGs sample, obtained by co-adding the spectra from their corresponding mosaics. Comparisons with previously published data are included. An analysis of the ionized gas component is performed, together with the techniques and methodologies implemented in order to derive the physical parameters of the integrated gas-phase of the galaxies sample. In § 6, I present a complete 2D spectroscopic study for a selected number of galaxies from the sample. Selected H II regions previously observed are compared with spectra extracted from the PINGs sample. A set of emission line maps calculated from each galaxy is presented, including a quantitative description of the 2D distribution of

the physical properties inferred from them. Then, a detailed, spatially-resolved spectroscopic analysis of the selected galaxies is performed, based on different spectral samples extracted from the full IFS mosaics of the galaxies. Several diagnostic diagrams and the state-of-the-art abundance diagnostic techniques are used to obtain the 2D distribution of the physical properties and chemical abundances of the selected sample. Finally, in § 7 I present the general conclusions of this dissertation, including some planned paths of future investigation.

THESIS CONTENT

The whole thesis is not included in astro-ph due to file size limitations.

The full contents can be found at:

<http://www.dspace.cam.ac.uk/handle/1810/224843>

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